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Advances in Electrochemical Micromachining of Silicon: Towards MEMS Fabrication

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Abstract

In this work, a significant step towards the fabrication of very high aspect-ratio complex microsystems by silicon electrochemical micromachining in HF-based electrolytes (ECM) is given. High aspect-ratio MEMS structures, with different shape and dimensions, consisting of inertial free-standing masses equipped with comb-fingers and suspended by springs from the substrate were fabricated by exploiting advanced features of the ECM technology.

Keywords: MEMS, silicon micromachining, electrochemical etching;

1. Introduction

The ElectroChemical Micromachining of silicon in HF-based solution (ECM) is a recently proposed bulk microstructuring technology combining advantages of both dry (high flexibility) and wet (low cost) traditional micromachining tools [1, 2]. Among the main features of ECM are worthy to be mentioned the possibility of changing the etching anisotropy [3] as well as the high aspect-ratio of viable structures [4]. Such features allow an enhanced flexibility in silicon microfabrication to be achieved, even with respect to dry etching tools.

In this work the ECM technology has been pushed to the fabrication of very high aspect-ratio free-standing MEMS structures.

2. MEMS Structure Fabrication by ECM

The fabrication of MEMS structures by electrochemical micromachining is performed according to the technological main steps schematically shown in Fig. 1. An *n*-type silicon wafer, with (100) orientation and

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a 200-nm-thick silicon dioxide layer on top, is patterned by standard photolithography with the layout of the structure to be fabricated. The pattern is firstly transferred to the silicon dioxide layer using a BHF solution and then to the silicon substrate surface using a KOH (25% wt) solution, the latter additioned with isopropanol to increase the etching uniformity -Fig. 1 (a)-. The oxide, layer, which acts as masking layer during the KOH etching step, is then removed from the silicon substrate surface using a solution 1:1 (vol) HF: Ethanol -Fig. 1(b)-. The replica of the structure layout grooved into the silicon substrate surface (seed points) is exploited for controlling silicon dissolution during the next electrochemical etching step.

The electrochemical etching (ECE) step is carried out under back-side illumination of the silicon substrate using a 5% (vol) HF-based solution, additioned with 1000 ppm (0.1%) of Sodium Lauryl Sulfate (SLS) surfactant as a wetting agent. The ECE consists of two distinct phases: an initial anisotropic phase -Fig. 1 (c)-, and a final isotropic phase -Fig. 1 (d)-. The anisotropic phase is exploited to deep etch the pattern into the silicon substrate. This phase ends as soon as a given depth is reached. At this stage the fabricated structures are still attached to the substrate. The next isotropic phase is exploited to etch the fabricated structures at their bottom and, in turn, release them from the substrate. Surfactant molecules adsorbed on the micromachined silicon surfaces are removed using a 1:5 (vol) HF:ethanol solution.

In order to provide the microfabricated free-standing structures with electrical actuation and/or capacitive sensing capabilities, the idea underlying the SCREAM (Single Crystal Reactive Etch and Metallization) process for MEMS fabrication was exploited [5]. A silicon dioxide layer obtained by thermal growth (100-200 nm thick) -Fig. 1 (e)- and a subsequent semi-conformal sputtering metal deposition (100-200 nm thick) -Fig. 1 (f)- are exploited to form highly conductive electrodes on the surface of the microfabricated structures.

The technological steps shown in Fig.1 allow MEMS structures with electrical actuation and/or capacitive sensing capabilities to be in principle fabricated by ECM technology.

The fabrication of high aspect-ratio MEMS structures by ECM requires the accurate design of the structure layout as well as an accurate control of the electrochemical etching of the layout both during the anisotropic and isotropic phase. A characteristic peak J_{ps} for a given voltage V_{ps} in the current density-voltage curve of the Si-HF electrochemical system allows to identify the ECM working region: $J_{etch} < J_{ps}$ and $V_{etch} > V_{ps}$. The etching current density value J_{etch} is given by the product of J_{ps} and the porosity (percentage of etched volume) of the structure to be fabricated. The value of J_{etch} is properly changed

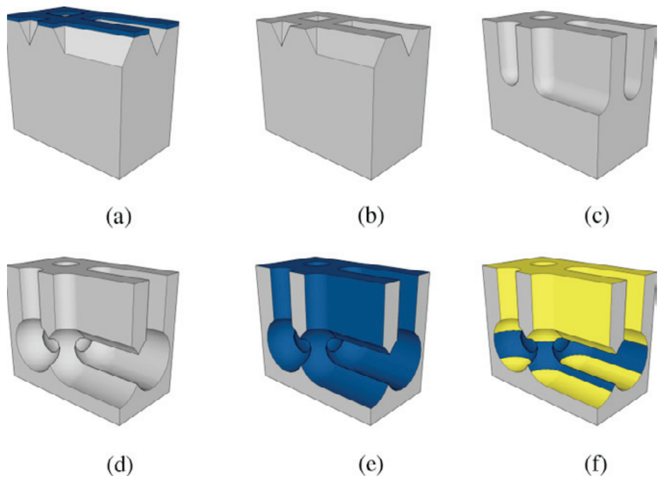
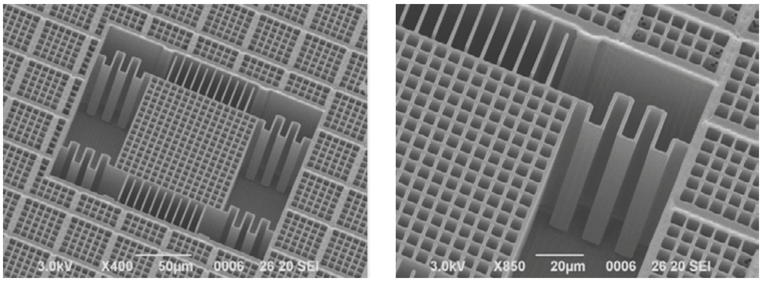


Fig. 1. Process flow for the fabrication of free-standing MEMS structures by means of the ECM technology. Definition of an array of holes and trenches (pattern) on the silicon surface (a) and (b); anisotropic electrochemical etching of the pattern into the substrates (c); release of the structures by isotropic etching (d); dry thermal oxidation (e); metallization by sputtering (f).



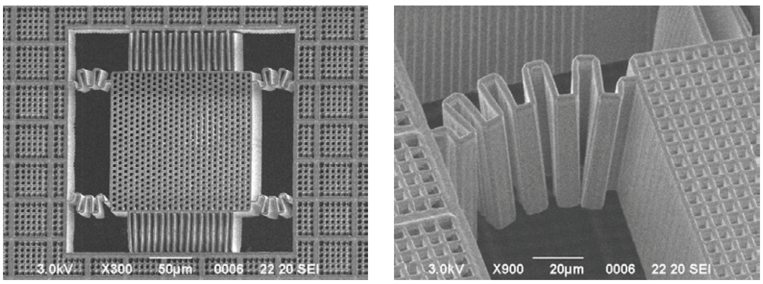
(a) (b)

Fig 2. SEM top view (a) and bird view (b) of a 100-µm-deep mass-spring free-standing structure fabricated by the electrochemical etching of silicon.

during the etching to compensate for the variation of the critical current density value J_{ps} as the etching progresses, due to the reduction of the HF concentration inside the pores caused by the diffusion-limited transport. The etching voltage value V_{etch} is also properly changed during the etching in order to optimize microfabrication results. The release of the etched structures is obtained by suddenly increasing both the etching current density value J_{etch} and the voltage value V_{etch} so as to make the etching switching from an anisotropic to an isotropic behavior. The isotropic etching of the silicon at the bottom of the microfabricated structures allows free-standing inertial masses equipped with comb-fingers as well as actuation springs to be obtained. In order to perfom the electrochemical deep etching of large areas and obtain the necessary room for the inertial mass displacement trhough springs deformation, sacrificial structures are exploited, which are removed during the isotropic phase of the etching. The use of sacrificial structures also allows lag-effect on the etching depth of silicon areas with different aspect-ratio to be avoided, which is a typical problem of DRIE tools [6].

Preliminary results on thermal oxidation and sputtering metallization of such high aspect-ratio structures highlight, on one hand, the conformal growth of the silicon dioxide layer during the thermal oxidation step even for structures with aspect-ratio value higher than 100, on the other hand, the discontinuity of the sputtered Au film in correspondence of the region subjected to isotropic etching, at the bottom of the anchor structure. These results are very encouraging as far as the possibility of achieving electrical isolation of metal electrodes according to the SCREAM process is concerned.

In Fig. 2 an example of mass-spring free-standing structure consisting of an inertial mass equipped with



(a) (b)

Fig. 3. SEM top view (a) and magnification (b) of a MEMS structure fabricated by ECM, after grow of a 1 µm thick silicon dioxide layer obtained by 6h wet thermal oxidation. Oxidation gives a preliminary proof-of-concept about feasible structure actuation.

comb-finger battery and connected to the surrounding anchoring structure by serpentine springs is shown. The mass is made of an array of holes with side of 5.3 μm and pitch of 6.8 μm. Comb-fingers and serpentine springs are 2-μm-thick and 100- μm-deep. The anchoring structure consists of a two-dimensional repetition of a square array of holes, with the same geometrical features as the inertial mass, surrounded by a 10-μm-thick wall that prevents connection of neighboring pores during the isotropic phase of the etching as well as formation of random macropores over non-patterned large areas during the anisotropic phase of the electrochemical etching.

A first proof of concept about ECM fabrication of MEMS is preliminarily given by demonstrating actuation of the microfabricated structures through wet thermal oxidation (Fig. 3). In fact, as silicon dioxide grows a volume increase of 54% occurs, which produces inertial mass displacement, with respect to their rest position, through spring deformation.

3. Conclusions

In this work, ECM technology has been pushed to the fabrication of MEMS structures. Free-standing inertial masses equipped with comb-finger batteries and suspended from the substrate by high aspect-ratio springs were for the first time successfully fabricated. A preliminary proof-of-concept about actuation of ECM fabricated microstructures through wet thermal oxidation was given. Experimental results foresee fabrication of high aspect-ratio MEMS structures by ECM with lower cost and higher flexibility, with respect to both wet and dry standard tools.

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